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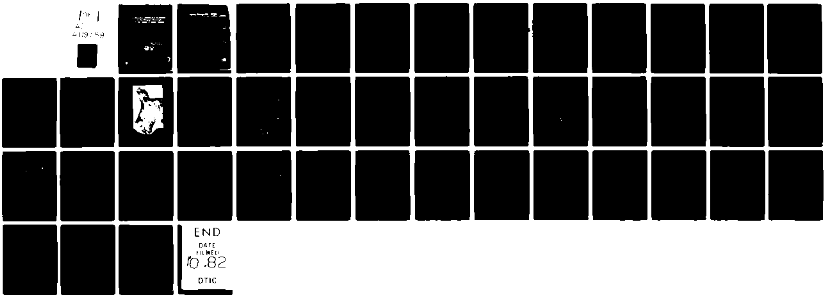

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Preliminary Geothermal Evaluation of the Mokapu Peninsula on the Island of Oahu, Hawaii

Prepared by
Hawaii Institute of Geophysics
Geothermal Assessment Program
Honolulu, Hawaii

for the

Geothermal Utilization Division
Public Works Department

JUNE 1982

NAVAL WEAPONS CENTER
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FOREWORD

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The report was reviewed for technical accuracy by Dr. J. A. [illegible] and Dr. Carl F. Austin.

Approved by
J. L. HORACEK
Capt., CEC, U.S. Navy
Public Works Officer
17 June 1982

Under authority of
J. J. [illegible]
Capt., U.S. Navy
Commander

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(U) Preliminary geological, geochemical, and geophysical field surveys were conducted on Mokapu Peninsula on the island of Oahu in an effort to determine whether sufficient indications of geothermal potential exist within or adjacent to the peninsula to justify further, more detailed, exploratory efforts. Results of the investigation indicate a very low probability of a geothermal resource beneath the peninsula.

A

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EXECUTIVE SUMMARY

Preliminary geological, geochemical, and geophysical field surveys have been conducted on Mokapu Peninsula on the island of Oahu in an effort to determine whether sufficient indications of geothermal potential exist within or adjacent to the peninsula to justify further, more detailed, exploratory efforts.

An evaluation of existing geologic data as well as recently completed mapping on Mokapu indicate that the peninsula is located on the edge of or immediately adjacent to the inferred caldera of Koolau volcano. There are at least three post-erosional volcanic vents located on the peninsula and several more form small islands adjacent to it. The age of this post-erosional activity has been estimated to be at least 400,000 years before present. The post-erosional events, on the basis of mineralogical and geochemical evidence, are not considered to have been a renewal of the older (1.8 million years before present) Koolau activity, but rather were a series of independent, short-lived eruptive episodes.

Geochemical investigations conducted within and around the Mokapu Peninsula included mercury-soil surveys and radon ground-gas surveys as well as a limited evaluation of groundwater chemistry. Numerous difficulties were encountered in the interpretation of the soil-gas geochemical data because of the high degree of cultural activity associated with the U.S. Marine Corps Air Station at Kaneohe; however, one area in the southwest quadrant of the peninsula was tentatively identified as a low-order geochemical anomaly in which observed levels of mercury and radon were both significantly higher than background values. These anomalous values were tentatively attributed to increased soil permeability or possibly to slightly elevated subsurface temperatures.

Groundwater sampling on Mokapu Peninsula was severely restricted because of the absence of wells within the study area and thus water chemistry analyses were limited to the Nuupia fish ponds. Samples obtained in the fish ponds were found to be seawater diluted with varying amounts of fresh groundwater. Although no thermal alteration of the water chemistry was evident for this area, an evaluation of existing groundwater chemical data for adjacent areas to the south and east of Mokapu suggests that some low-level thermal alteration may be present within shallow aquifers overlying the inferred Koolau caldera.

Schlumberger resistivity soundings were completed in three locations on the peninsula: KVS1, in the northeast quadrant within the Ulupau crater, KVS2 in the northwest quadrant along the main jet runway, and KVS3 in the southeast along Mokapu Road. At KVS1 a relatively high resistivity was encountered to a depth of approximately 20 meters below sea level, which was underlain by a basement resistivity of about 2 to 3 ohm-meters. At KVS2 and KVS3 similar resistivities of 2 to 3 ohm-meters were detected at much shallower depths (approximately equivalent to local sea level) below a thin, moderately resistive layer having an impedance ranging from 15 to 118 ohm-meters. Although the basement resistivity values are somewhat lower than would be expected for seawater-saturated basalt, and therefore could be interpreted as arising from a thermal anomaly, it is considered far more probable that the

resistivities observed correspond to a low-resistivity seawater-saturated clay layer underlying the peninsula.

In the context of the geothermal potential of the Mokapu Peninsula, the results of the present survey can be summarized as follows:

1. The geological data suggest that the post-erosional volcanism associated with the Mokapu Peninsula was of such a short duration and is of such great age that it is considered unlikely that significant remnant heat would be found beneath these structures. Although remnant heat may still be present within the magma chamber of Koolau volcano, there is presently no geologic evidence to substantiate its occurrence.

2. The geochemical data available indicate that one area within the peninsula may be slightly anomalous; however, no firm conclusions can be drawn concerning its relationship to a potential heat source. Limited groundwater geochemical data for the peninsula do not suggest the presence of thermally altered groundwater although some indication of groundwater anomalies have been identified several kilometers to the south of Mokapu Peninsula.

3. The results of geophysical surveys suggest that the peninsula is underlain by seawater-saturated clays at local ambient temperatures. The probability of there being an exploitable high-temperature resource beneath the Mokapu Peninsula is extremely low, and the probability for a low-temperature resource, at economically viable depths, is also very low.

I. GEOLOGY OF THE MOKAPU PENINSULA AND ADJACENT AREA

Malcolm E. Cox and John M. Sinton

INTRODUCTION

The island of Oahu was formed by the coalescence of two major shield volcanoes (Figure 1), Waianae in the west, active about 3.6 to 2.4 million years ago, and Koolau in the east, active about 2.6 to 1.8 million years ago (McDougall, 1964; Gramlich et al., 1971; Doell and Dalrymple, 1973). Both of these volcanic edifaces subsequently underwent extensive erosion that removed much of the shield structures above sea level. The ancient caldera of the Koolau volcano is indicated by both geological and geophysical evidence to be located in the Waimanalo-Kailua-Kaneohe area, where features such as intense dike intrusion and zones of hydrothermally altered lavas occur. The Koolau Range represents the remnants of a major northwest-trending rift zone and a minor southeast-trending rift zone, which extend outwards from the caldera structure. Along the Koolau Range the lavas of the inland (leeward) side of the shield, which were probably unaltered during formation, have been exposed because of the largely subaerial and marine erosion of the eastern flank of the shield.

The Koolau volcano appears to be typical of a Hawaiian volcano that has reached maturity. Hawaiian volcanoes are formed from thin lava flows (approximately 1-meter thick) erupted from a summit caldera complex (3- to 5-kilometer diameter) and along two or three radiating rift systems. Dikes are plentiful in the vicinity of the caldera and in the rift zones, where the frequency is often on the order of several hundred per kilometer. The early shield-building stage of activity forms most of the mass of the volcano (95 to 99%) and usually lasts for a period of 0.5 to 1.5 million years. The lavas formed during the shield-building stage are

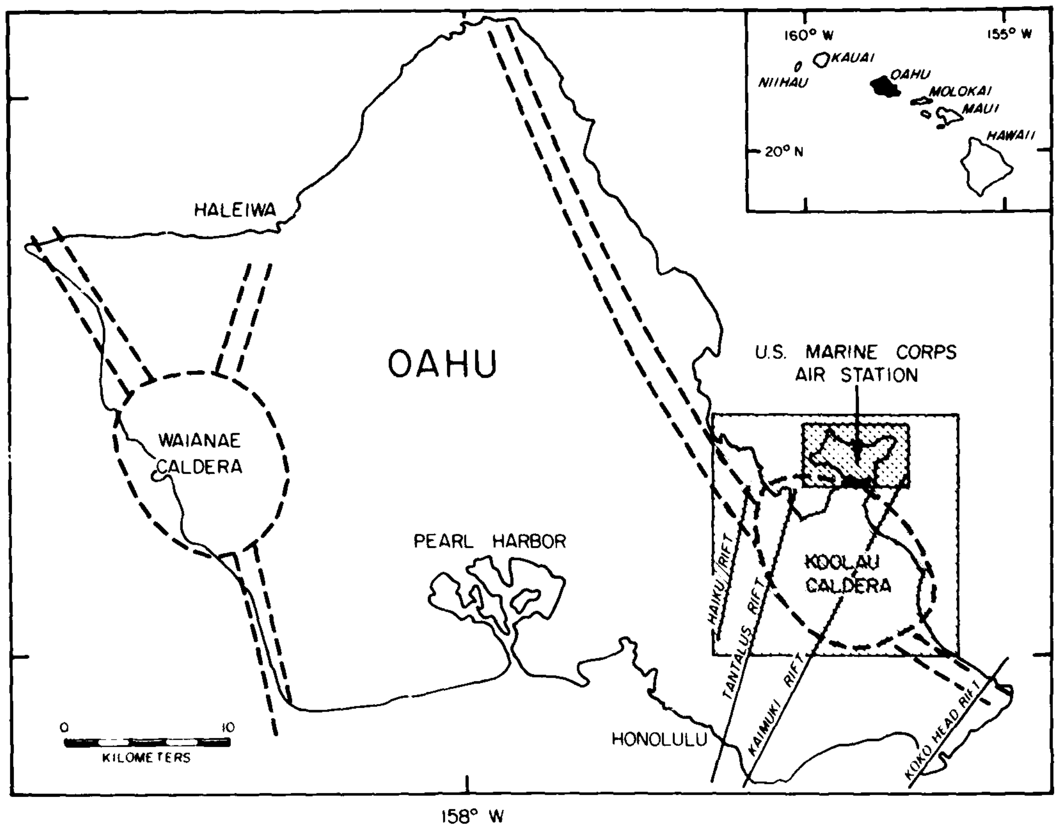

FIGURE 1. Map of Oahu Showing Location of Survey Areas. The locations of the Koolau and Waianae calderas and associated rift zones are shown by broken lines. Minor fracture zones giving rise to the Honolulu Volcanic Series centers after the interpretation of Winchell (1947) are shown by unbroken lines.

mainly of tholeiitic basalt composition, such as those found in the Koolau Range. These basalts are relatively rich in silica and deficient in alkalies, such as sodium and potassium; pigeonite is present in some tholeiitic lavas and olivine phenocrysts are common (Macdonald and Abbott, 1977). In the latter part of the shield-building stage, eruptions become less frequent and the caldera is filled by lavas whose composition grades to a more viscous alkalic basalt that is comparatively poorer in silica and richer in alkalies, and is deficient in low-Ca pyroxene. The alumina-silica ratio for tholeiitic basalt is <0.3 and that for alkalic basalt is >0.3. The alkalic basalts are generally present as a thin layer on the top of the volcanic ediface. Although such a layer has not been observed at Koolau, it may have been removed by erosion; a few small, isolated, outcrops of lava that are apparently alkalic do exist and suggest that the alkalic stage of the Koolau volcano was not well-developed by the time the eruptions ceased (Macdonald and Abbott, 1977).

KOOLAU VOLCANO

The Koolau volcano formed a caldera approximately 12 kilometers in length and at least 6 kilometers in width (Figure 2); based on geological criteria, Macdonald and Abbott (1977)

GENERALIZED GEOLOGY

Waimanalo-Kaneohe area

	Artificial fill.	
	Calcareous sedimentary material: coral, coral rubble, dunes and recent beach sand.	
	Alluvium.	
Honolulu Volcanic Series	Flows and minor breccia.	Olivine nephelinite and nepheline melilitite.
	Spatter, cinder and breccia.	
	Vitric crystal lithic tuff.	
Kailua Volcanic Series	Dike complex.	Olivine tholeiitic basalt.
	Lava flows.	
Koolau Volcanic Series	Dike complex.	Olivine tholeiitic basalt.
	Lava flows.	
	Possible throat breccia.	
	Nephelinite.	Honolulu Volcanic Series vents.
	Melilitite.	
	Basanite.	
	Swamp.	
	Ridge of Koolau Range.	
	Approximate outline of Koolau caldera (Macdonald and Abbott, 1977).	

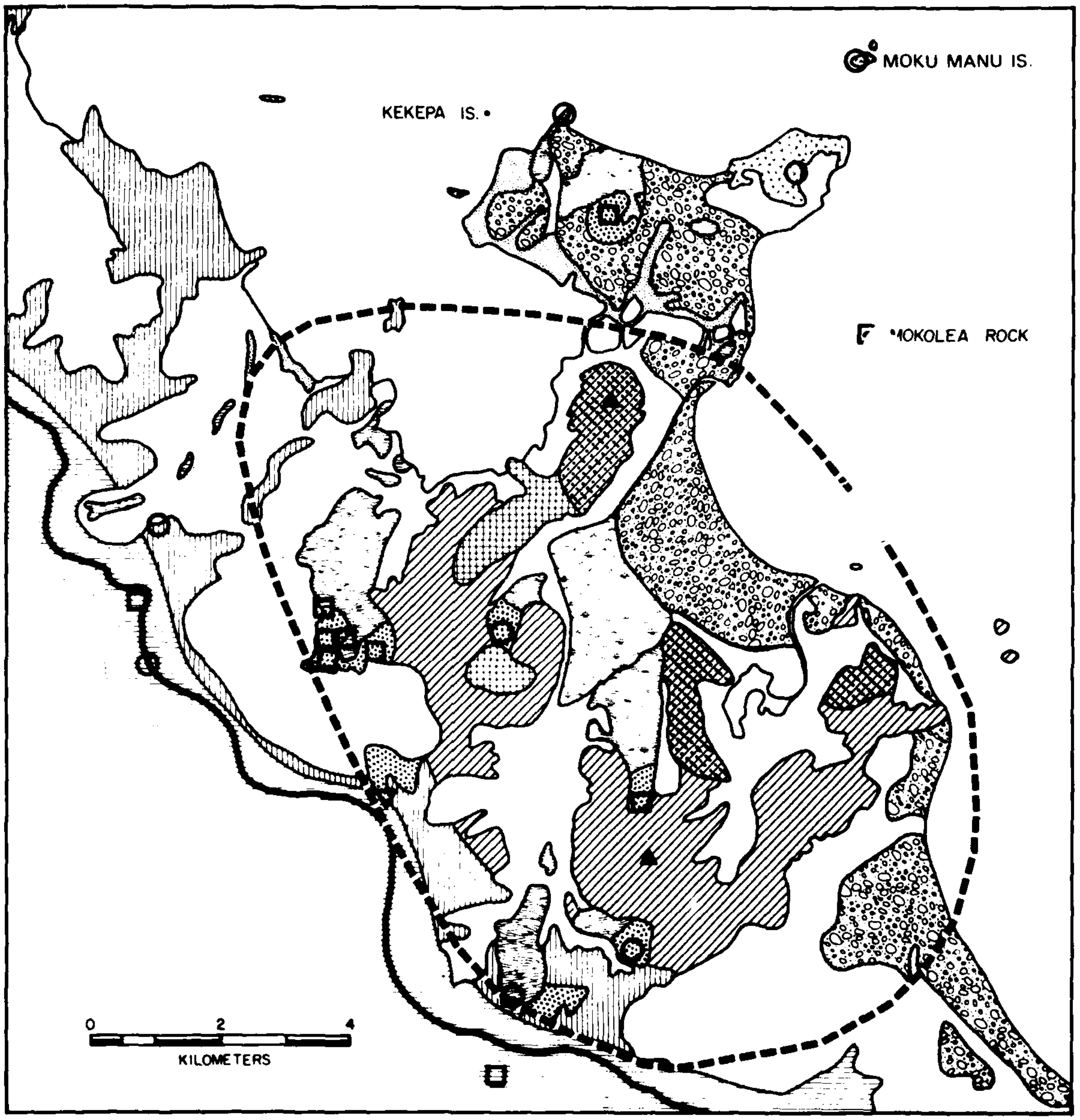

FIGURE 2. Generalized Geology of the Waimanalo-Kaneohe Area (After Stearns, 1939; Wentworth and Hoffmeister, 1939 and Takasaki, et al., 1969).

consider that the boundary of this caldera extended from southeast of Waimanalo to northwest of Kaneohe. These data are compatible with the results of gravity studies (Strange, et al., 1965) which defined a roughly circular Bougner anomaly (to >310 mgal) probably representing a mass of dense material below the caldera, within the same area. Seismic refraction studies also indicate the existence of a dense intrusive mass beneath the Kaelepulu Pond-Kawainui Swamp area (Figure 3) which is interpreted to be near the center of the caldera. The top of this intrusive plug is at a depth of about 1,600 meters and it is estimated to have a width of around 6 kilometers to a depth of 3 to 4 kilometers (Adams and Furumoto, 1965). Furumoto (1976) considered that the deeper magma chamber of the Koolau volcano could be approximated by a buried vertical cylinder, with dimensions estimated from gravity data of 16-kilometer diameter and 10 kilometers in vertical height. Two areas of hydrothermally altered breccia (Figure 2) to the west and northwest of Kawainui Swamp are part of the Koolau Volcanic Series and were interpreted to be throat breccias marking the main vent of the Koolau volcano (Stearns and Vaksvik, 1935), although this conclusion has been questioned by subsequent authors (e.g., Macdonald and Abbott, 1977).

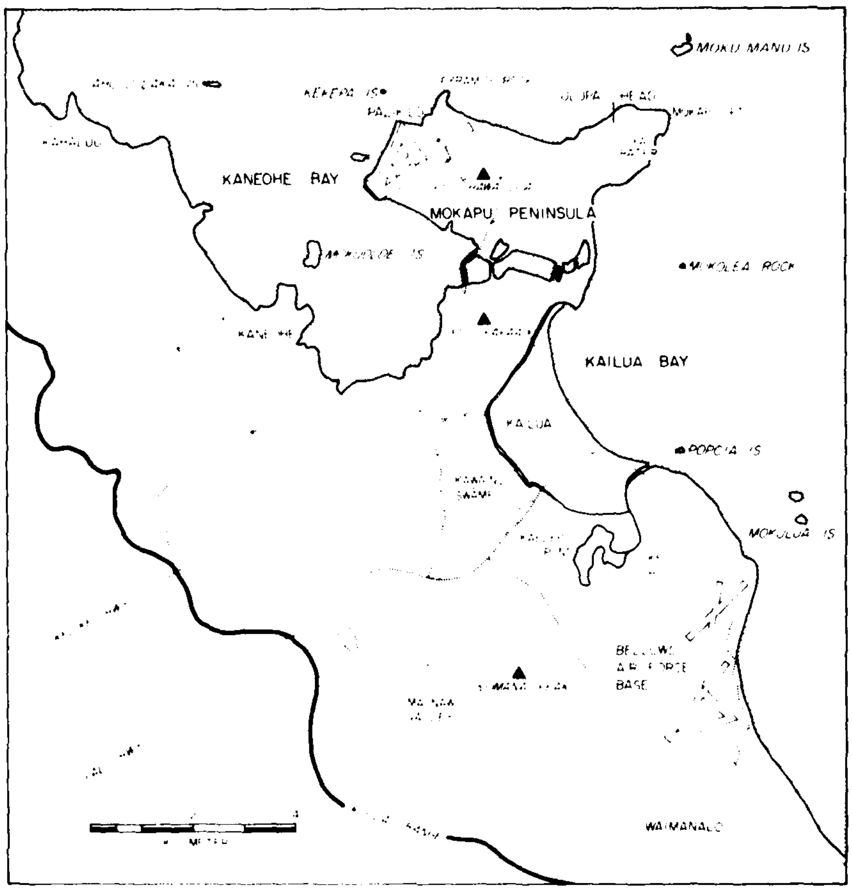

FIGURE 3. Location Map of Waimanalo-Kaneohe Area. Roads are shown by unbroken lines; the crest of the Koolau Range by broken line.

The mass of the Koolau volcano that remains exposed above sea level is rather uniform throughout, and in the caldera area is composed of two conformable formations: the older Koolau Volcanic Series lavas and dike swarms, and the younger Kailua Volcanic Series lavas and dikes (Stearns and Vaksvik, 1935; Stearns, 1939). The Kailua Volcanic Series rocks are part of the Kailau volcanism and are the caldera-filling lavas. The rocks are exposed in the vicinity of Waimanalo-Kailua (Figure 3) and consist of pahoehoe and aa flows up to 18 meters in thickness. Although these rocks are of tholeiitic composition, similar to the Koolau Volcanic Series rocks, they are amygdaloidal and contain considerable amounts of secondary minerals within vesicles and joints.

The Koolau Range itself is mainly composed of a large number of thin lava flows of tholeiitic basalt around 0.5 to 4.0 meters thick. These flows are intruded by dikes and sills and associated irregular stringers. Some of the dikes are large enough to have moderately coarse crystallinity. The dikes and sills of the Koolau Range can be considered in two groups (Wentworth and Jones, 1940): those of the dike complex that parallels the Koolau Range (the fissure system being marked by swarms of subparallel dikes over a zone 3 to 9 kilometers wide), and those scattered outside the complex. The dike complex is considered to be the main rift zone through which the magma for the Koolau flows reached the surface. Most of the dikes are 0.25 to 1.2 meters thick and cut the lava flows, which commonly have dips of 4 to 10 degrees, almost at right-angles. The location and attitude of dikes appear to have been mainly determined by the fracture systems in the rocks. A characteristic dike swarm can be observed in the H-3 highway cutting through the Puu Papaa part of the Mokapu Peninsula opposite the Kaneohe Marine Corps Air Station (KMCAS).

POST-EROSIONAL ACTIVITY

The alkalic stage of Hawaiian volcanism is characteristically followed by a cessation of volcanic activity for an extended period during which erosion takes place. (The removal by erosion of such a significant amount of the Koolau volcanic shield during this period was probably facilitated by the hydrothermal alteration resulting from rising magmatic gases that the massive caldera-filling flows had experienced (Macdonald and Abbott, 1977) as well as the fracturing associated with the caldera structure and rift systems.) This period of inactivity is followed on some Hawaiian volcanoes by a post-erosional period of renewed, but decreased, activity from a series of scattered volcanic centers. In the Kailua-Kaneohe area this rejuvenation is part of the Honolulu Volcanic Series activity that followed an inactive period on the order of 1.2 to 1.5 million years (e.g., Lanphere and Dalrymple, 1980).

The post-erosional lavas are typically silica undersaturated melilitites, nephelinites, and basanites although some alkalic olivine basalts also occur. Melilitites are feldspar-free lavas with abundant melilite as well as nepheline. These lavas mainly have SiO_2 contents less than 39.7 wt. %, compared to 39.7 to 42.1 wt. % for nephelinite (Clague and Frey, 1981) and 42 to 48 wt. % for basanite and alkali basalt. Nephelinites resemble basalts and usually contain olivine, but contain nepheline in place of feldspar; basanites are transitional between nephelinite and alkalic basalts, containing both nepheline and plagioclase feldspar (Macdonald and Abbott, 1977). In contrast, Koolau tholeiitic basalts have 48- to 52-wt. % SiO_2

(Wentworth and Winchell, 1947). Several of the Honolulu Volcanic Series lavas in the Koolau caldera area contain ultramafic xenoliths, mainly of dunite, lherzolite, and clinopyroxenite (Jackson and Wright, 1970).

The Honolulu Volcanic Series rocks were formed from at least 37 vents dispersed across southeastern Oahu, and at least 20 separate vents have been recognized in the immediate area of the Koolau caldera (Figure 2). The distribution of these vents does not appear to have any relation to structures of the Koolau volcano and are not considered to be part of the Koolau activity (Macdonald and Abbott). Several early authors (e.g., Stearns and Vaksvik, 1935; Winchell, 1947), however, considered that the distribution of Honolulu Volcanic Series vents followed minor fracture zones perpendicular to the major rift zones of Koolau volcano. The interpretation of Winchell (1947) is shown in Figure 1. While some linearity of vent locations does occur, we believe, based on available evidence, that only the Koko Head rift is a reasonable postulation. Dating of the Honolulu Volcanic Series rocks by K-Ar and Rb-Sr techniques indicates that the post-erosional basalts were erupted less than about 0.6 (Lanphere and Dalrymple, 1980) or 0.8 million years (Gramlich, et al., 1971) ago, and it is possible that this activity may not yet have ended.

GEOLOGY OF THE MOKAPU PENINSULA

The northern part of the Mokapu Peninsula, on which the U.S. Marine Corps Air Station is situated (Figure 4), is largely formed of post-erosional rocks of nephelinite and nepheline melilitite composition. The physical form of the erupted lavas, however, depend on the conditions under which they were erupted. The two major types of post-erosional cones found on the Mokapu Peninsula are tuff cones and cinder or spatter cones. Tuff cones, for example Ulupau, are broad bowl-shaped structures formed by hydromagmatic or phreatomagmatic explosive eruptions where rising magma has come into contact with groundwater or seawater-saturated lava or reef rock. The resulting steam explosions eject fragments of both the original country rock as well as new juvenile material from the eruptive vent; the ejecta usually form circular ramparts around the main vent and accumulate most heavily on the leeward side of the cone. Cinder and spatter cones are formed from explosions within the conduit that propel molten ejecta upwards; cinder and molten lava droplets fall back near the vent building narrow, steep-sided cones with smaller central craters. The Pleistocene history of formation of the Mokapu Peninsula has been described by Stearns and Vaksvik (1935), Stearns (1939), Wentworth and Hoffmeister (1939), Winchell (1947), Stearns (1966), Jackson and Wright (1970) and Macdonald and Abbott (1977). Those studies also describe some features of the peninsula that are no longer visible because of the present intensive cultural activity, and in some cases provide conflicting reports.

At least three volcanic vents have been recognized on the peninsula and several more form adjacent small islands. Those on the peninsula are Pyramid Rock (nephelinite) in the northwest, Puu Hawaiiloa (melilitite) in the center, and Ulupau Head (nephelinite tuff) in the northeast (Figures 2 and 5). Pali Kilo may also be a separate volcanic vent although it is considered to be associated with Pyramid Rock.

FIGURE 4. Aerial View of the U.S. Marine Corps Air Station on Mokapu Peninsula. Scale 1 cm = 240 m (U.S.G.S., 1978).

GENERALIZED MAP OF ROCK TYPES ON KMCAS

Artificial fill

Calcareous and sedimentary material, including sand dunes

Alluvium

Lithic, vitric Ulupau tuff of nephelinite composition

Nephelinite flows

Melilitite flows

Melilitite cinder and spatter

Roads

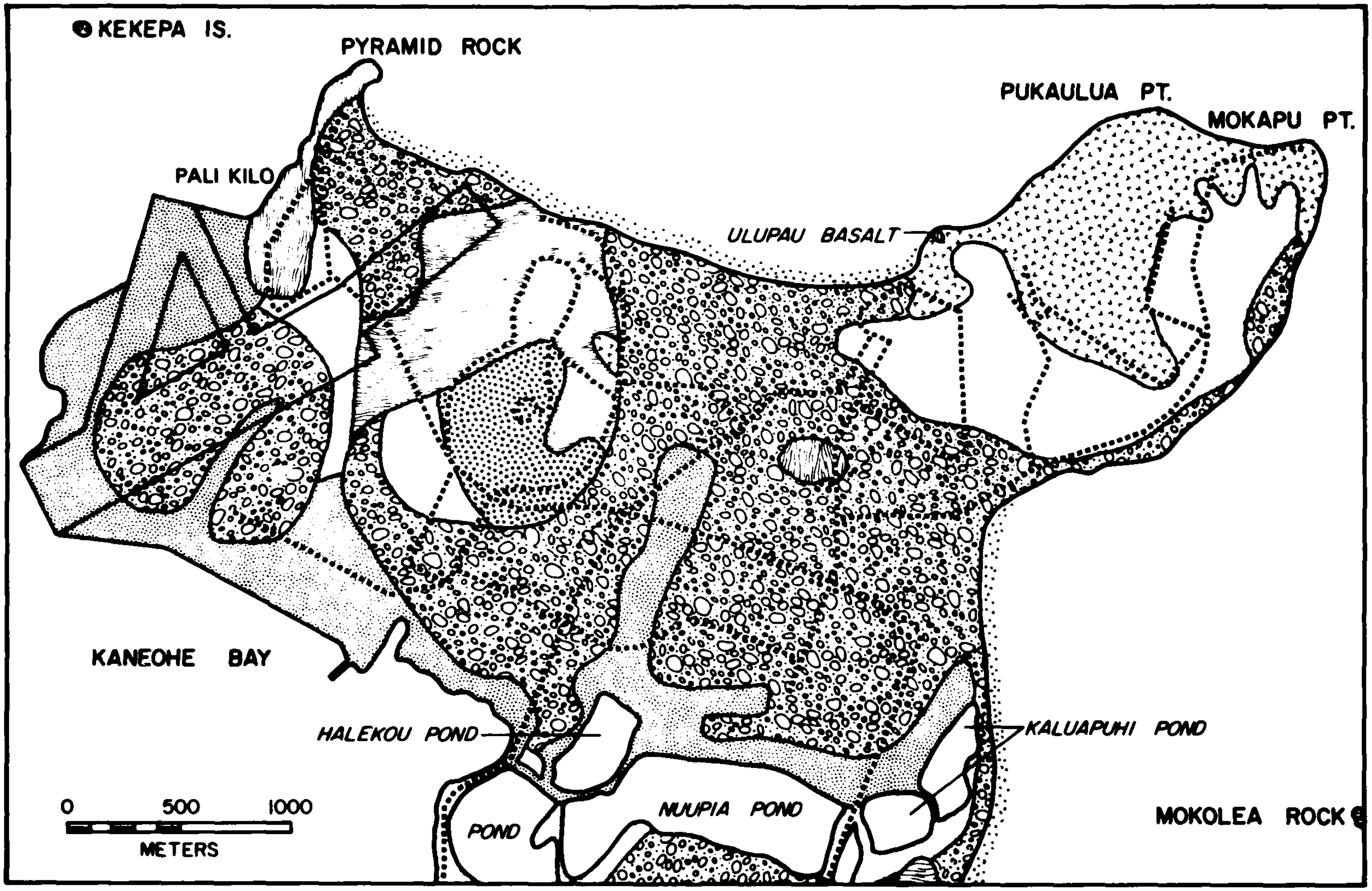

FIGURE 5. Generalized Map of Rock Types at the KMCAS on the Mokapu Peninsula (After Stearns, 1939; Wentworth and Hoffmeister, 1939; and Takasaki, et al., 1969).

Pyramid Rock appears to be a deeply eroded vent in which the feeder dike and breccia have been exposed and may be the oldest eruptive center on the peninsula (Stearns and Vaksvik, 1935; Winchell, 1947; Lanphere and Dalrymple, 1980). (Stearns and Vaksvik (1935), however, considered Pyramid Rock to be a massive columnar jointed flow.) Lava from Pali Kilo is petrographically identical to that from Pyramid Rock. Geochemical data, in Clague and Frey (1981), indicated that the two lavas are very similar in composition although that from Pali Kilo is slightly differentiated (lower Co, Ni, Sr; higher Zr, Ba, Zn) compared to Pyramid Rock. These data suggest that these lavas all represent the same eruptive event although the focus of activity may have shifted somewhat during eruption. The data are also consistent with Pali Kilo lavas that have their source at the Pyramid Rock vent (Macdonald and Abbott, 1977).

Puu Hawaiiloa, in the center of the peninsula is a cinder cone, which gave rise to a series of lava flows totaling greater than 30 meters thick to its north. These flows possibly also underlie parts of the west and center of the peninsula. Both Pyramid Rock and Puu Hawaiiloa probably formed during a period when the stand of the sea was about 90 meters below its present level. A terrace at about 30 meters elevation on Puu Hawaiiloa is suggestive of being produced by marine erosion during the subsequent Kaena higher stand (+29 meters) of the sea (approximately 320,000 years before present). Although Ulupau tuffs are believed to overlie the Puu Hawaiiloa flows, which would make them younger than that activity, three small outcrops of (Puu Hawaiiloa?) basalt in the eastern half of the peninsula have been reported (Figure 5) that were possibly emplaced after the formation of Ulupau Crater (Stearns and Vaksvik, 1935; Wentworth and Hoffmeister, 1939; Winchell, 1947). The outcrops to the southwest and south of Ulupau Crater are of nephelinite and nepheline-melilitite composition, respectively, and are vesicular, flow-banded, and of extrusive character. That outcrop on the coast immediately west of Ulupau Crater ("Ulupau Basalt") is reported to be of nephelinite composition and to be massive with irregular jointing (Wentworth and Hoffmeister, 1939).

Ulupau Crater was initially formed, probably just below sea level, from an offshore submarine vent that broke through calcareous reef formations. The deep erosion on the crater's northern and eastern sides by wave action suggests that the cone is older than the subsequent stand of the sea (Laie) at about 21 meters above its present level. This theory is further supported by the deposits of fossiliferous marine sediments within the crater, apparently formed during breaching of the crater on the east and intrusion by the sea. The tuff that forms the cone is similar to other secondary palagonitic tuffs in southeast Oahu (e.g., Diamond Head, Koko Head) and is considered to be derived from a nepheline basalt magma (Winchell, 1947).

The flat area of the peninsula to the southwest of Ulupau Head is partly composed of reef rock formed by an earlier fringing reef during a period of higher sea level. A sea level of about 3.7 meters above the present has been estimated at 32,000 years before present (Macdonald and Abbott, 1977). The present sea level has formed wave-cut terraces and sea cliffs in the tuff beds on both the northwest and southeast shorelines of Ulupau Head.

The small island of Mokolea Rock in Kailua Bay to the east of the peninsula (Figure 2) is a massive nepheline melilitite lava, probably a flow, and presumably associated with a cone now destroyed by erosion (Stearns and Vaksvik, 1935). The lava is similar in composition to the outcrop of basalt reported 2.5 kilometers to the south-southwest of Ulupau Crater (Winchell, 1947). The small island of Kekepa just west of Pyramid Rock is reported to be nepheline basalt (Stearns, 1939) but is mapped as calcareous material by Wentworth and Winchell (1947). The double island of Moku Manu to the northeast of the peninsula is the eroded remnant of a tuff cone and associated nepheline basalt flow (Stearns and Vaksvik, 1935; Winchell, 1947). Both of the latter were probably formed during the same period as Ulupau Head.

COMPOSITIONAL ZONING IN HONOLULU VOLCANIC SERIES

Petrological work by Jackson and Wright (1970) indicated that the Honolulu Volcanic Series rocks in southeastern Oahu are compositionally zoned with respect to the Koolau shield. Subsequent work on a larger number of samples (Clague and Frey, 1981) has, however, shown that there is no well-developed zonation of lavas, except that alkali olivine basalts are mainly restricted to the Koko Head rift. Also, melilitites have now been determined to exist on the apron of the Koolau caldera well outside the study area.

The Honolulu Volcanic Series rocks within the study area are of both nepheline melilitite and nephelinite compositions (Figure 2), and no obvious zoning within the caldera area is apparent. There is, however, on the Mokapu Peninsula a tendency for nephelinites to occur in the northern part and nepheline melilitites to occur in the southern part. Consequently, it is now believed (Clague and Frey, 1981) that there is no relationship between age and composition of the Honolulu Volcanic Series lavas.

Broad zoning of the composition of the contained xenoliths is, however, apparently still a valid concept. Jackson and Wright (1970) noted that xenoliths in the area of the Koolau caldera are mainly dunite, and grade to lherzolite at intermediate distance and on the apron of the shield, with garnet pyroxenite and peridotite also occurring on the apron. No zonation of xenoliths within the Mokapu Peninsula lavas is reported. The zoning of xenolith composition is considered by Jackson and Wright to be caused by lateral and vertical heterogeneities in the mantle beneath Oahu due to the voluminous eruption of the Koolau tholeiitic basalts.

AN EVALUATION OF THE GEOTHERMAL POTENTIAL OF MOKAPU BASED ON GEOLOGIC EVIDENCE

As noted above, the Honolulu Volcanic Series rocks are not considered to be a renewal of the Koolau activity, but to have formed within the periphery of the caldera of the Koolau volcano. The locations of vents are presumably related to zones of weakness, perhaps including minor rift structures, but whether the overall locations of vents are controlled by linear or radial structures, or are more random, has not been unequivocably determined. The Honolulu Volcanic Series lavas in the vicinity of the Koolau caldera are all notably rich in magnesium and iron and undersaturated with silica, and petrological evidence suggests that the source of the magma is at a considerably deeper level (approximately 100 kilometers) than the Koolau magma (60 to 80 kilometers) (Jackson and Wright, 1970; Clague and Frey, 1981). Ratios of $^{87}Sr/^{86}Sr$ (Powell and Delong, 1966; Lanphere and Dalrymple, 1980) also indicate that the Honolulu Volcanic Series rocks are not derived from a parent magma common to the Koolau

Volcanic Series, either by igneous differentiation or by carbonate syntexis. These studies also show that although difficulties arise using the K-Ar dating method because of excess argon from the ultramafic inclusions, the age of the eruptive activity on Mokapu must be at least 400,000 years before present.

The formation of a geothermal system under Hawaiian conditions appears to involve circulating groundwaters obtaining their heat from hot intrusive rock or the heated lava pile immediately surrounding it. In the case of areas of active or recently active volcanism, the intrusive material would probably be dike swarms and larger intrusive bodies such as plugs at relatively shallow depth. In the case of an older volcanic center, the heat source would more likely be a larger, deeply buried, intrusive body.

The existence of a thermal resource below the Mokapu Peninsula is not considered to be promising from the aspect of a hot intrusive mass. Although the Honolulu Volcanic Series activity is young relative to the Koolau activity, it is rather old in terms of remnant heat considering the limited size of the eruptions, their apparently short duration, and the indicated depth from which the magma was derived. Furthermore, evidence suggests that Honolulu Volcanic Series lavas were erupted relatively rapidly from great depths without the development of a long-lived, steady-state magma chamber. Thus, there would not have been any significant shallow source of heat associated with Honolulu Series volcanism. Also of importance is the high rock porosity and resultant rapid circulation of saline water, around hot intrusive masses that is likely to occur below the peninsula. Considering these factors it is highly improbable that there is a mass of intrusive material of sufficient size, and retaining sufficient heat, at shallow enough depth (1 to 3 kilometers) to influence the near-surface thermal environment. Further, even if an elevated geothermal gradient did exist at a substantial depth (i.e., within the Koolau shield lava underlying the Honolulu Series Rocks forming the Mokapu Peninsula) it is uncertain whether the hydrogeological conditions of the peninsula would enable circulation of groundwater to any appreciable depth to become heated. Of note, however, is the fact that the dense mass below the Koolau caldera, as indicated by gravity surveys (Strange, et al., 1965), has some continuation below the Mokapu Peninsula. If some anomalous elevation of temperature at depth below the peninsula does occur, it could heat the saline water intruding the aquifer at depth. Under such conditions low-order anomalous temperatures could develop, but it is considered unlikely that existing conditions would enable either entrapment of the water at depth or some recirculation to shallower levels.

The possibility of still hot intrusive material existing below the Koolau caldera has been suggested (Furumoto, 1976) and should be considered. The Koolau caldera area possesses many features similar to the caldera area of the older Waianae volcano on Oahu. Geothermal investigation in that area strongly indicates that above ambient subsurface temperatures occur in association with the older caldera boundary (Cox, et al., 1979). Similar features exist in the Koolau caldera, and of note are elevated temperatures (30°C, i.e., approximately 8°C above ambient) in two shallow groundwater wells near the caldera boundary. Of importance is the size of the intrusive mass associated with this caldera, which increases the possibility of heat retention. A further consideration is the renewal of activity in the area of the caldera with the Honolulu Volcanic Series eruptions, which in places appear to have broken through the pre-existing intrusives of the Koolau caldera.

In summary, the development of a geothermal system is more likely below the Koolau caldera than on Mokapu Peninsula; structure and fractures are very important in groundwater migration, and intrusive material is the most likely source of heat to circulating groundwaters. It is possible that some form of low-temperature system could have developed in the area (including below Mokapu Peninsula), but based on geological criteria there is little likelihood of economic temperatures being encountered. The only way to definitively determine subsurface temperatures and hydrological conditions is by deep drilling (approximately 2,000 meters).

II. GEOCHEMICAL SURVEYS OF MOKAPU PENINSULA AND ADJACENT AREAS

Malcolm E. Cox, Donald M. Thomas, and Kevin E. Cuff

INTRODUCTION

From the aspect of conducting geochemical surveys, KMCAS presents certain difficulties: notably the high degree of cultural activity, and the absence of groundwater drill holes to enable water sampling for geochemical evaluation. Several surveys of a preliminary nature were, however, carried out on the peninsula: concentrations of mercury (Hg) in soil, concentrations of radon in shallow ground gas were measured, and samples of surface water from the fish ponds were analyzed. To further assist in understanding the environment of the peninsula, the Hg survey was extended to the adjacent Waimanalo-Kaneohe area, and previously existing groundwater chemistry for that area was assessed in a geothermal context.

MERCURY-SOIL SURVEYS

The association of elevated concentrations of Hg with geothermal fluids is well-established, and surveys measuring Hg concentrations in soil are now commonly used as a geothermal exploration technique (e.g., Matlick and Buseck, 1976; Capuano and Bamford, 1978). The basis of using this element is that Hg can be released from geothermal systems because of its high volatility at elevated temperatures and its ability to migrate upwards through overlying rock strata. Within lower temperature areas and near to or at the surface, Hg may then become fixed and can produce concentration patterns in soils that reflect the existence and location of subsurface fluids at elevated temperatures.

The concentration of Hg in soils can, however, be influenced by a variety of other factors. In areas of thick soil or alluvial cover over geothermal systems, the distribution of Hg may be more closely related to permeable zones in the underlying rock rather than to the actual heat source. Properties of the soil also influence the retention of Hg, which can be bound to the soils as elemental Hg, as inorganic compounds or, more frequently, as organo-complexes. Thus the content of organic material in the soil can be a major influence on the observed Hg concentrations (e.g., Klusman and Landress, 1978; Cox, 1981), as can the degree of development of the soil, clay content, soil acidity, and cultural interferences. Consideration of such factors can, however, enable the delineation of areas of anomalous Hg concentration that may be associated with geothermal activity.

The method followed in this survey was to collect samples of soil from depths of approximately 15 centimeters and seal them in plastic bags; after air drying in the laboratory, the soils were sieved to less than 0.5 millimeters, and the Hg concentration was determined by gold film analyzer (McNerney et al., 1972). Concentrations of Hg are reported as parts per billion (ppb), and the precision of analysis was within ±5%.

Mercury Survey in the Waimanalo-Kaneohe Area

Sampling was conducted within the area of the eroded caldera of the Koolau volcano (see Figure 2), and sample locations are shown in Figure 6. A soil Hg survey had previously been conducted in this area (Souto, 1978), in which concentrations up to 1,400 ppb were reported. The anomalous zones of the Hg survey by Souto, defined by contours of 400 and 600 ppb, are also shown in Figure 6 with the results obtained from this survey contoured at intervals of 50 ppb.

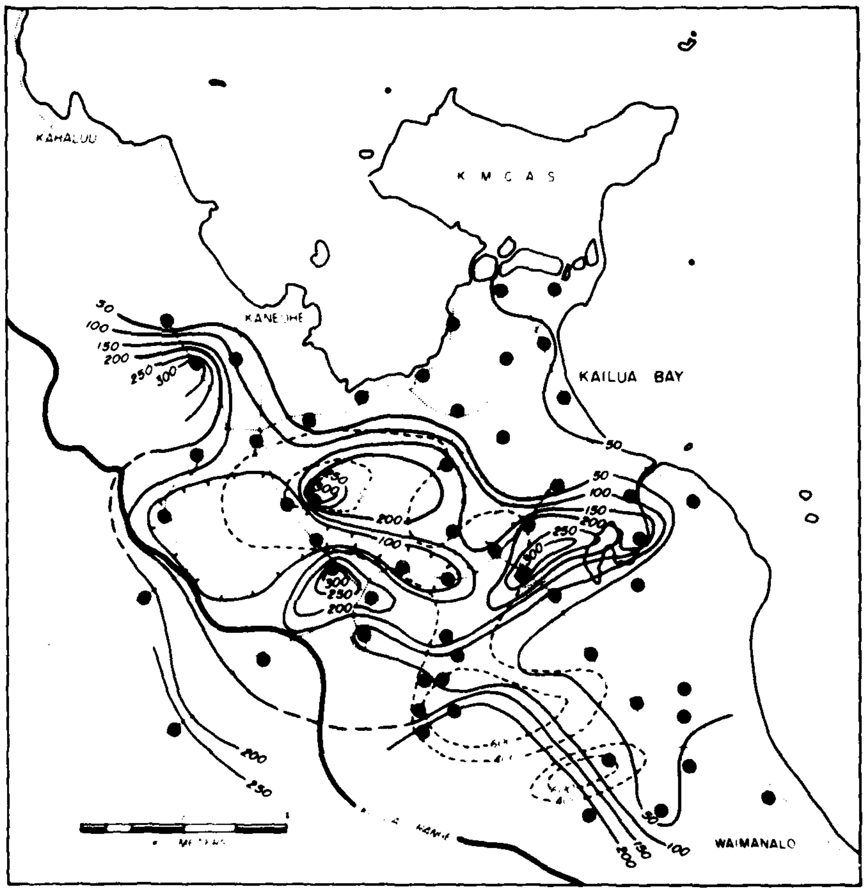

FIGURE 6. Distribution of Soil Hg Concentrations in the Waimanalo-Kaneohe Area, Contoured at 50-ppb Intervals. Solid circles show sample locations. The anomalous zones (400 and 600 ppb) of the Hg survey by Souto (1978) are shown by dashed lines.

Concentrations of Hg ranging from 12 to 365 ppb are lower (approximately half) than those determined by Souto (1978) (his method of analysis is not reported), however, with respect to the relative variations within each of the surveys, there is some correlation between the observed anomalous zones; we do not, however, consider that the high values to the south of the survey area represent an extension of the anomaly. It should be noted also that the distribution of Hg values partly reflects differences in soil type within the region and appears to be strongly influenced by the organic content, which is related to variations of rainfall within the area. (This effect tends to be confirmed by a comparative series of seven soil samples taken in a geothermally inactive area on the southern side of the Koolau Range, from the tuff cone of Diamond Head, and northward up Palolo Valley to near the top of the Koolau Range. The sandy soils derived from the marine tuff of Diamond Head had values of 34 to 56 ppb and Hg concentrations increased northward up Palolo Valley with changes in soil type and increasing precipitation and organic content (159, 180, 209, and 270 ppb)).

Whereas the Hg concentrations in excess of 150 ppb are generally considered to be anomalous, the high values in the west and southwest of the area (>200 ppb) are believed to reflect the higher rainfall and greater organic content of the soil close to and over the Koolau Range. Low concentrations (<50 ppb) occurring along the coastal plain are largely in response to the calcareous marine sediments and sandy soils in those areas. This condition is especially so in the Waimanalo area to the southeast. The intervening area has transitional concentrations, but the elongate central zone of concentrations of greater than 150 ppb (to over 300 ppb) is considered to be anomalous. It is significant that this anomaly occurs over the zone below which the magma body of the Koolau volcano is believed to exist (e.g., Strange,et al., 1965); the anomaly is also close to, or over, several of the Honolulu Volcanic Series vents in the center of the caldera. This anomaly also encompasses an area of Kailau Volcanic Series rocks that are characterized by hydrothermal alteration. *Macdonald and Abbott* (1977) note that such alteration extends at most only 50 or 60 meters into the adjacent lavas, and thus not beyond the caldera boundary. Hydrothermal alteration minerals and clay minerals occurring in the Keolu Hills basalts (over which the eastern end of the anomaly extends) have been studied (Fujishima and Fan, 1977); joints and vesicles in these amygdaloidal basalts contain quartz, calcite, zeolite, and other secondary minerals, and the basalts have a chloritized appearance. Fujishima and Fan (1977) hypothesized that low-temperature subsurface alteration may still be occurring in the southeastern part of the Koolau caldera and note the existence of above-ambient temperatures in groundwater wells in that area.

The extensive alteration in parts of the Kailua Volcanic Series is presumably caused by low-temperature (approximately 70 to 80°C) alteration over extended periods associated with the past volcanic activity. Low-temperature reactions have altered olivine to serpentine or talc, and much of the pyroxene to chlorite; the resultant silica released by this alteration has been deposited throughout the rocks as quartz, chalcedony, or opal (Macdonald and Abbott, 1977). An area where such secondary mineralization is well-developed is Olomana Peak (Figure 3) to the south of the Hg anomaly.

While it is possible that elevated Hg concentrations could be associated with the secondary mineralization and hydrothermal alteration of the Kailua Volcanic Series basalts, the zone of anomalous values is not believed to be entirely a result of that. Fresh basalts in the area have variable Hg concentrations, commonly 5 to 15 ppb, and up to 35 ppb in weathered lavas. Samples of unweathered dike rock and amygdaloidal lava of the Kailua Volcanic Series had Hg concentrations of 1 to 2 ppb, and samples of zeolite amygdules have concentrations of 2 to 5 ppb.

In summary, the anomalous zone central to the Waimanalo-Kaneohe area is considered to be of some significance as indicated by Hg concentrations of at least twice the indicated background and is believed to be associated with, at most, a low-order thermal anomaly probably rising from the central plug of the Koolau volcano.

Mercury Survey on the Mokapu Peninsula

Soil samples from the KMCAS on Mokapu Peninsula (Figure 7) were collected and analyzed as described above, and values are contoured in Figure 8. The Hg concentrations on the peninsula are generally lower than in the adjacent Waimanalo-Kaneohe area and range from 7 to 222 ppb. Low values (<50 ppb) similarly tend to occur around the peripheries of the peninsula and in association with sandy or calcareous soils; Hg concentrations within the Ulupau tuff are also low, ranging from 24 to 38 ppb. (These concentrations are lower than those measured in three samples of similar tuff-derived soils from each of Diamond Head and Koko Head cones, which range from 34 to 84 ppb.)

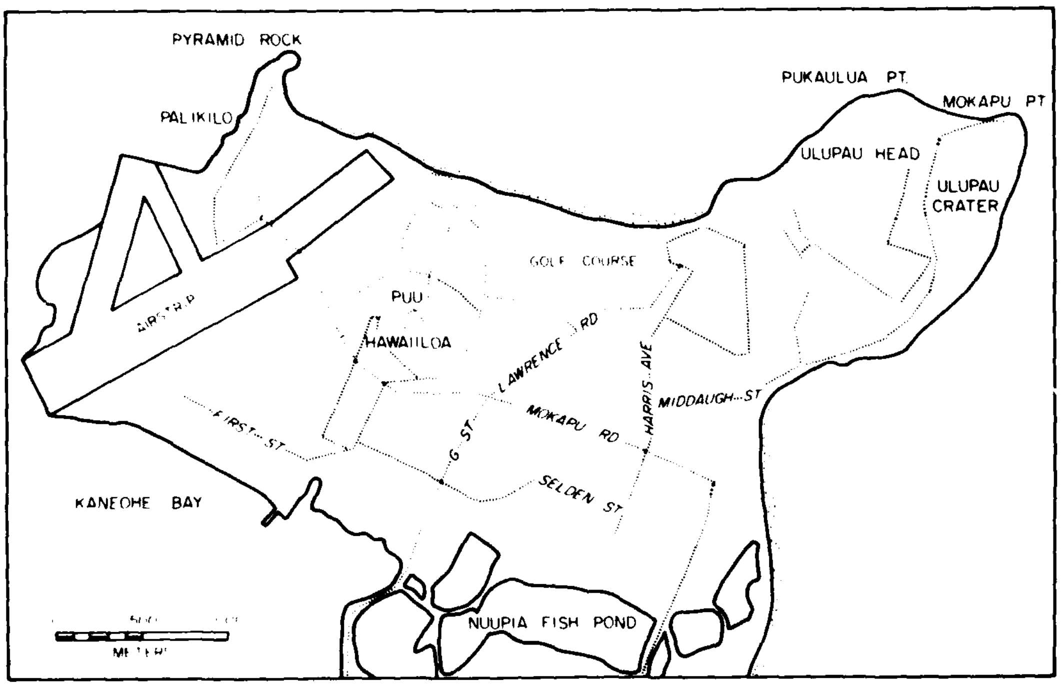

FIGURE 7. Major Roads and Physical Features on KMCAS on Mokapu Peninsula.

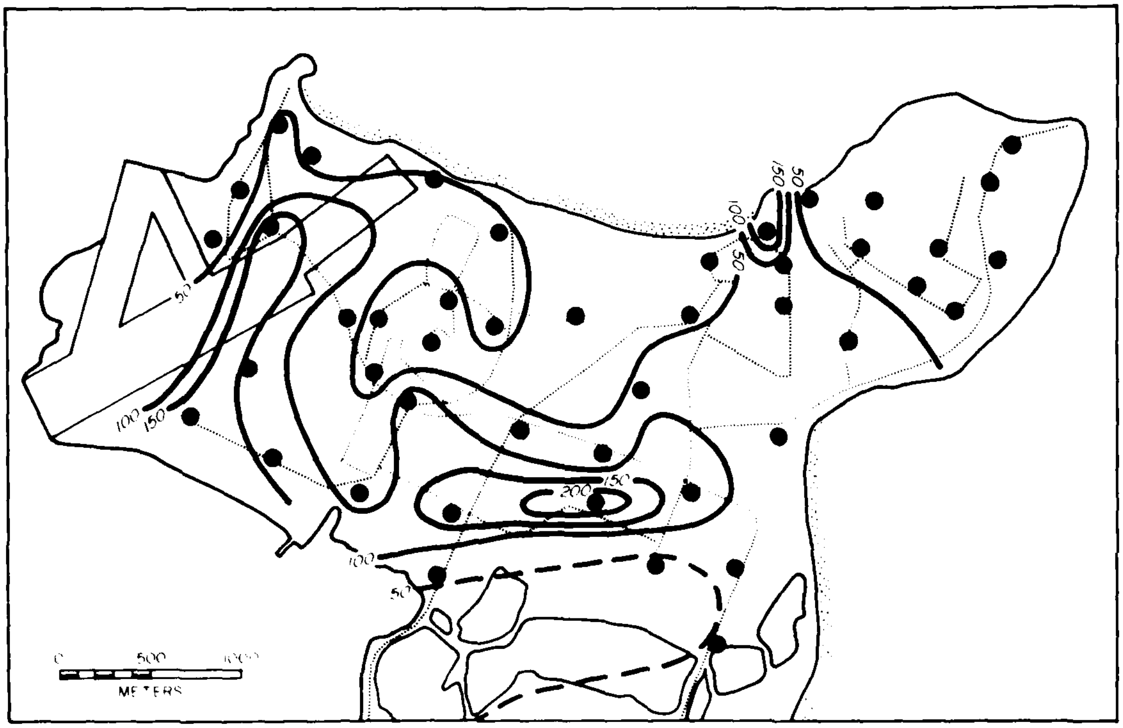

FIGURE 8. Distribution of Soil Hg Concentrations on Mokapu Peninsula. Contoured at 50-ppb Intervals. Heavy dashed line is inferred contour.

Two zones of higher values (>100 ppb) occur in the center and southwest sections of the peninsula, which are possibly due to a higher clay and organic content in the soil in those areas (those in the southwest are formed of introduced artificial fill); it is also possible that the higher values in the southwestern zone, to the south of the airstrip, are superficial and the result of contamination from aircraft exhaust carried downwind. (Elevated concentrations of Hg are often associated with fossil fuel products (U.S.G.S., 1970)). The cause of the elongate zone of high values near the center of the peninsula is not known, but appears to be anomalous as low values occur over adjacent areas of similar soils. An isolated high value (245 ppb) was determined in the northeast of the peninsula near to a drainage ditch; because of its isolation and location it is most likely the result of introduced contamination or other cultural effects.

Overall, Hg in soils within the KMCAS is of relatively low concentration but a small zone based on four samples does appear anomalous with values of 2 to 3 times background. Because of its limited extent and location, it is not considered to be caused by thermal conditions, and overall the variations in Hg concentration appear to be caused by influences such as soil properties and cultural activity and not the result of a geothermal influence.

GROUND RADON SURVEYS*

Radon (Rn) is an alpha-particle emitting radioactive gas in the uranium and thorium decay series. Radon forms naturally in the ground by radioactive decay of its parent nuclide, radium. Of the three major isotopes of Rn, Rn-222, which has the longest half-life (3.8 days), is the isotope that is most frequently detected. Measurements of the concentration of Rn in ground gas at shallow depth can be used to delineate areas where there may be an upflow of ground gas (and elevated concentration of Rn) caused by increases in permeability such as faults and zones of fracturing, or that may be driven by elevated subsurface temperatures. Such surveys have been successfully applied to geothermal exploration in continental areas characterized by thick soil and alluvial cover (e.g., Nielson, 1978), in active volcanic areas such as Puna on the island of Hawaii (Cox, 1980), and in the Waianae area of Oahu, an eroded caldera similar to that of Koolau (Cox, et al., 1979).

The method is described elsewhere (e.g., Fleischer and Magro-Campero, 1978; Cox, 1980), but, in summary, small strips of alpha-particle-sensitive film are buried in the ground in inverted 250-milliliter containers at depth of approximately 30 centimeters. The films were exposed in the field for a period of approximately three weeks. After collection and processing, the number of alpha-particle collision tracks can be counted and the results presented as (tracks) $T \cdot 10^{-2}/cm^2hr$. The emission of Rn from the soil immediately below the measuring device is similarly determined in the laboratory to obtain background values for the different soil types. Concentrations of Rn in ground gas measured in the field during the present survey are presented as multiples of the background emanation from the soil.

The variation in both the type and thickness of the soil on the peninsula produced a variation of determined background (i.e., Rn emanation from the soil itself) of over 400%, which complicates the evaluation of the results. Consequently, in an attempt to make the results more meaningful in terms of anomalies, the Rn concentrations measured in the field are presented as "X" the determined background. Studies in other parts of Hawaii (Cox, et al., 1979; Cox, 1980) indicate that, in assessing an area for geothermal potential, measured Rn values of 5 to 6 X background indicate increased permeability and low-order heat; values of >10 X indicate high permeability and significant heat. Values of 3 to 4 X background indicate low permeability only, with some enhanced movement of ground gas. Values ≤1 X background suggest a possible downflow of ground gas or very low permeability.

The results for the Mokapu Peninsula, presented as X background are shown in Figure 9. Values of ≤1 X background occur over much of the peninsula, but noticeably within areas that are overlain by recent beach deposits and alluvium. These low values are probably caused by the relatively low permeability of this material, but also could be caused by a shallow depth to the water table. The distribution of Rn values does suggest a trend of higher concentrations of Rn in ground gas associated with the volcanic structures on the peninsula. In the east, the two zones of ≥1 X background may suggest some structural linearity from Ulupau Crater to the southwest; in the west, the zone ≥1 X is associated with the northwest flank of Puu Hawaiiloa cinder cone and the weathered lava flow of Pali Kilo. The highest values are 3.9 X background.

*Regarding radon surveys, see U.S. Patents 3,303,085 (February 7, 1967) and 3,665,194 (May 23, 1972) of the Terradex Corp

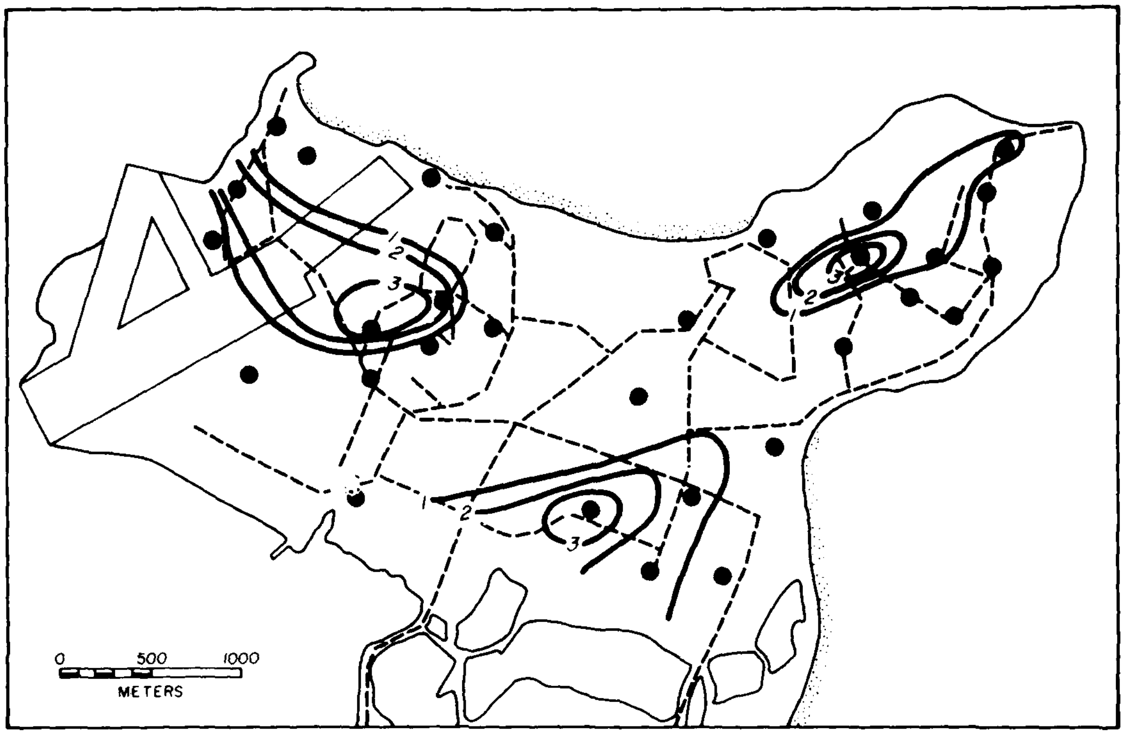

FIGURE 9. Distribution of Values of Rn in Shallow Ground Gas, Presented as Rn Concentration X Background (i.e., Rn Emanation From Different Soil Types). Contoured of intervals of 1 X background.

It is not presently possible to fully explain the results obtained during the current study on the basis of the data available from this area, and several interpretations could be placed upon them. This problem is largely because of the extreme variability of the soil type and substrata within the area and the consequent necessity for a larger number of measurement stations than were feasible during the current study. However, even though we consider these surveys to be of a preliminary nature, we believe that the zones of higher radon emanation represent areas of relatively higher permeability, which result from a combination of both the properties of the surface material and fracture or pore space permeability of the substrata, and are not related to thermal conditions. The increases are of very low order and of limited extent and do not indicate the presence of any geothermal activity.

GROUNDWATER CHEMISTRY

Available groundwater chemical analyses were examined for indications of alteration of chemistry that could be related to water-rock reactions associated with elevated temperatures. Unfortunately, only a limited number of groundwater wells and tunnels in the Waimanalo-Kaneohe area had chemistry available, and no groundwater wells are reported to have been developed on the KMCAS. Four samples of water were taken from the fish ponds separating KMCAS from the mainland to observe if any hydrothermally altered groundwaters may be entering the ponds.

Chemical analyses for the area are presented in Table 1 and the locations of the sources are shown in Figure 10. Also shown in Figure 10 are the temperature and the Cl/Mg ratio of the waters. The ratio of Cl/Mg has been successfully applied in regional geothermal assessment in Hawaii as a qualitative indicator of the existence of groundwater-rock reactions at above-ambient temperatures (Cox and Thomas, 1979); where the ratio is >15.0 (that of average seawater) it is considered to be indicative of increased water-rock reaction.

The different chemical types of groundwater in Hawaii display characteristic ranges of Cl/Mg values. For the survey area, plotting of the chemical analyses on trilinear Piper diagrams shows the following water types (see Figure 10 for sampling locations within the survey area):

$NaHCO_3$: A, H, J;

$CaNaHCO_3$: B, C, D;

$CaNaHCO_3Cl$: E, L, M, N;

$CaMgNaHCO_3$: I;

Na Cl : K, O, P, Q, R.

High elevation, cooler groundwaters have the lowest Cl/Mg ratios, commonly ≤4.0. The ratio increases with the degree of saline water mixing, reaction with marine and terrestrial sediments, and previously formed hydrothermal minerals. Many of the groundwaters exhibit Cl/Mg ratios of fresh cool groundwaters that have undergone limited water-rock reaction (e.g., A, B, C, D, E, F, N, L, I); some suggest very low-temperature reaction with rock or hydrothermal minerals (e.g., H and K, and possibly M). Well K (2042-13), near the coast at Waimanalo, demonstrates saline water infiltration of the marine sediments. The Cl/Mg ratios of the fish pond samples (O, P, Q, R) all indicate the water to be largely seawater with various degrees of mixing of fresh groundwater.

The chemical types of water are also shown in the plot of Ca/Mg versus Cl ion concentration (Figure 11). For this figure the mean compositions of stream water, seawater, and deep, high-temperature, geothermal water from well HGP-A (on the island of Hawaii) form the points of a triangle. The occurrence of samples within this triangle can give an indication that some thermal processes may have altered the water chemistry. Three wells from other areas are plotted for comparison: the shallow test well Geothermal #3, Puna, Hawaii, near HGP-A; and two groundwater wells with above-ambient temperatures, from Lualualei Valley of the Waianae caldera in western Oahu. Of the Koolau caldera samples, only K, I, and possibly F suggest some thermal alteration. To a lesser degree this indication may also be the case for wells H and E. The latter also occurs within the Kailua mercury anomaly. The samples from the fish ponds are shown to be essentially seawater.

TABLE 1. Chemical Analyses of Groundwater, Waimanalo-Kaneohe Area.

Analysis in parts per million.

Site[a]	Well No.	Name	pH	°C	Depth(m) Well/Water	Elev. (m)	Na (Na+K)	K	Ca	Mg	SiO_2	Cl	F	SO_4	HCO_3 + CO_3	Fe	Mn	Cl/Mg	Date
A	2750-02	Kahaluu Well	7.6	--	-- --	--	(27.9)		5.0	8.1	19.8	36.0	--	8.2	105.	0.2	--	4.4	1937
B	2550-01	T-64	6.2	22.5	-- --	--	13.0	0.6	6.6	4.3	30.0	17.0	0.	3.4	43.	0.01	0.005	4.0	1975
C	2448-01		7.7	--	-- --	--	(10.7)		6.5	4.6	2.0	14.0	0.1	8.2	46.	<0.1	<0.1	3.0	1961
D	2348-02	Kuou Well 1	7.5	--	-- --	--	(10.2)		23.0	6.7	24.0	20.0	0.1	7.2	71.	<0.1	0.	3.0	1955
E	2246-01	Kahanaiki Well	7.6	--	-- --	--	(28.9)		27.9	9.5	41.6	30.0	0.3	18.4	68.	0.1	0.	3.2	1953
F	2245-01	Training Schl. Well	7.0	--	-- --	--	(14.6)		13.7	11.8	20.4	37.0	0.2	11.2	93.	0.1	--	3.1	1958
G	2142-03	Bellows A.F.B.	--	26.1	12.5/2.2	6.1	--	--	--	--	--	--	--	--	--	--	--	--	1962
H	2043-01	Waimanalo 408	7.3	30.0	163.7/9.6	7.9	28.0	1.1	14.0	2.8	22.0	25.0	0.1	5.4	84.	--	--	8.9	1970
I	2043-02	Waimanalo 420	6.9	25.0	85.3/8.8	43.3	36.0	1.0	12.0	6.8	35.6	27.0	0.05	10.0	148.	0.3	0.03	4.0	1971
J	2042-05	Waimanalo 420	--	30.0	137.2/--	--	--	--	--	--	--	--	--	--	--	--	--	--	1966
K	2042-13	Waimanalo 420-1A	7.4	25.0	48.8/--	15.2	920.0	36.0	150.0	110.0	26.0	1700.0	0.2	220.0	224.0	0.	0.01	15.5	1975
L		C&C Waimanalo	8.0	--	-- --	--	(15.4)		16.3	6.3	12.0	18.0	0.1	8.7	37.0	0.1	0.	2.9	1953
M		Haiku Tunnel	--	--	-- --	--	(12.4)		5.7	2.4	23.2	14.0	0.1	3.3	39.0	0.3	0.	5.8	1948
N		Plantation Waimanalo	7.9	--	-- --	--	(13.4)		17.2	7.0	22.4	22.0	0.1	8.7	42.0	0.1	0.	3.1	1953
O	Pond #1	N.E. Nuupia Pond	--	--	-- --	0.	12534.	400.	407.	1432.	3.0	19110.	--	2433.	--	--	--	[illegible]	1981
P	Pond #2	Halekou Pond	--	--	-- --	0.	9250.	400.	407.	1412.	2.9	19412.	--	2433.	--	--	--	13.8	1981
Q	Pond #3	Nuupia Pond	--	--	-- --	0.	10566.	429.	423.	1366.	2.9	18809.	--	2257.	--	--	--	13.8	1981
R	Pond #4	Kaluapuhi Pond	--	--	-- --	0.	13684.	588.	404.	1822.	3.5	25498.	--	3227.	--	--	--	14.0	1981

[a] Location on map in Figure 10.

Source of data: U. S. Geological Survey, Hawaii - B, G, H, K.
Hawaii Dept. of Health - A, C. D, E, F, I, L, M, N.
Macdonald, 1973 - J,

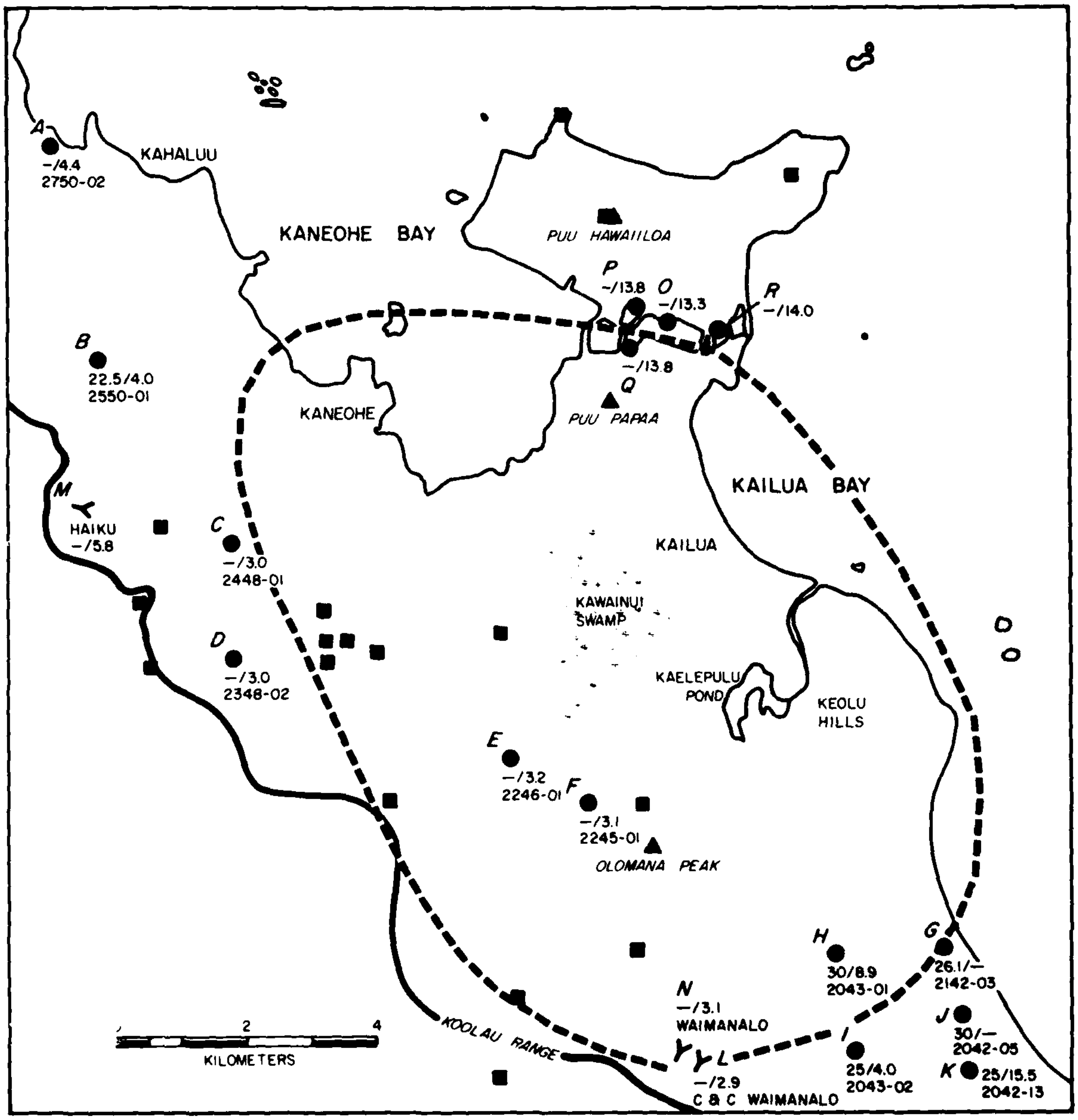

FIGURE 10. Location of Groundwater Sources From Which Chemical Has Been Assessed. Solid circles are wells; "Y" funnels. The locations of four samples of pond water collected in this study are shown. Open triangles are locations of Honolulu Volcanic Series vents (excluding offshore islands); heavy dashed line is boundary of Koolau caldera (after Macdonald and Abbott, 1977); heavy solid line is crest of Koolau Range. Upper numbers near each source: left = temperature, right = Cl/Mg; lower number is identification number of name.

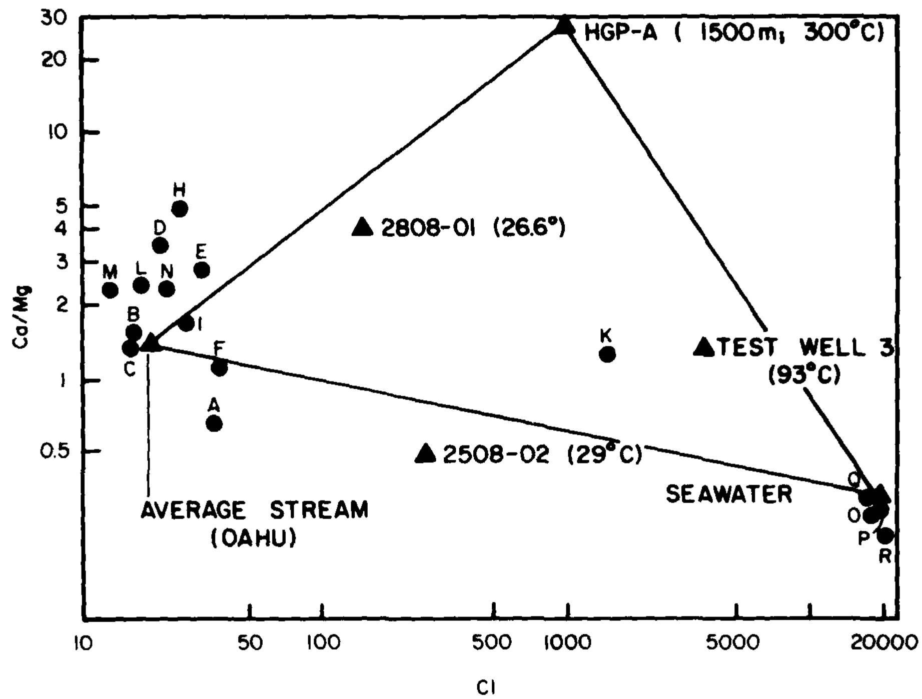

FIGURE 11. Plot of Ca/Mg Versus Cl Ion Concentration for Waters in the Area.

The chemistry of these waters shows them to be typical of a variety of groundwaters found in Hawaii. The most obvious indications of enhanced water-rock reaction are for wells in the Waimanalo area, where above-ambient groundwater temperatures have been measured, which is believed to be near the boundary of the Koolau caldera. The alteration of the water chemistry is undoubtedly also enhanced by the presence of hydrothermal minerals, which were largely produced by the now-extinct volcanic activity.

CONCLUSIONS FROM GEOCHEMICAL SURVEYS

Only broad conclusions can be drawn from these surveys because of the difficulties introduced by the high level of cultural activity and the lack of subsurface data. On the Mokapu Peninsula, anomalies of both Hg and Rn are of relatively low order and limited extent and provide little indication of the existence of geothermal heat. The pattern of the Rn anomalies suggests the possibility of a relative increase in the permeability of the substrata, possibly in association with the volcanic structures. The Hg anomalies are believed to be caused by cultural activity.

A more positive indication of geothermal activity (although also of low order) occurs within the Koolau caldera. The Hg anomaly central to the area is believed to be geothermally related and possibly associated with the underlying intrusive mass of the caldera. Low-temperature groundwater reactions apparently are occurring at least along the southeastern boundary of the caldera, and perhaps in several other locations (e.g., locations of groundwater sources M, E, and F). The existence of groundwater with temperatures of approximately 5°C above ambient in the southeast have been reported.

In summary, low-order thermal anomalies are indicated to occur within or associated with the boundary of the Koolau caldera. Several of the anomalies, central to the caldera and on Mokapu Peninsula, coincide with Honolulu Volcanic Series vents. However, the existence of anomalous thermal conditions cannot be confirmed. The data currently available indicate that the known thermal anomalies and the indicated ones are all of very low order and would most likely be of insufficient potential to consider developing.

III. DC RESISTIVITY SOUNDINGS ON THE MOKAPU PENINSULA, OAHU

Barry R. Lienert

INTRODUCTION

In March 1981 three Schlumberger soundings were performed on the Mokapu Peninsula on the northeast coast of Oahu. The locations of these soundings are shown in Figure 12. The data were collected using a Bison 2390 receiver and transmitter, which utilizes a chopping frequency of 0.1 hertz to reduce the effect of background noise. Copper-copper sulfate non-polarizing electrodes were used for the receiver electrodes. Interpretation of the resulting apparent resistivities was performed using the inversion routine described by Anderson (1979). The measured apparent resistivities appear in Figures 13, 14, and 15, and the layered models obtained by inverting these data are shown in Figure 16 (resistivities are given in ohm-meters). The theoretical curves corresponding to the models in Figure 16 are the solid curves in Figures 13, 14, and 15, whereas the circles represent the measured apparent resistivities. All three soundings yield low basement resistivities of about 2 to 3 ohm-m.

For soundings KVS2 and KVS3, the interpreted depth to the low-resistivity basement corresponds closely to the depth to sea level implying that the basement is saltwater-saturated material. The KVS3 data also imply a rise in resistivity at a depth of about 100 meters below sea level. The interpreted resistivities above sea level for the two soundings are both 15 ohm-m with both sections capped by a thin (<1 meter) layer of higher resistivity material, which is probably unconsolidated dry soil. Sounding KVS1 also includes a layer of higher resistivity material (85 ohm-m) extending from just above sea level to about 20 meters below it in addition to the 15-ohm-m and 2-ohm-m layers. The similarity between the three geoelectric sections in Figure 16 is surprising considering the variability in the outcropping rocks close to the three sites.

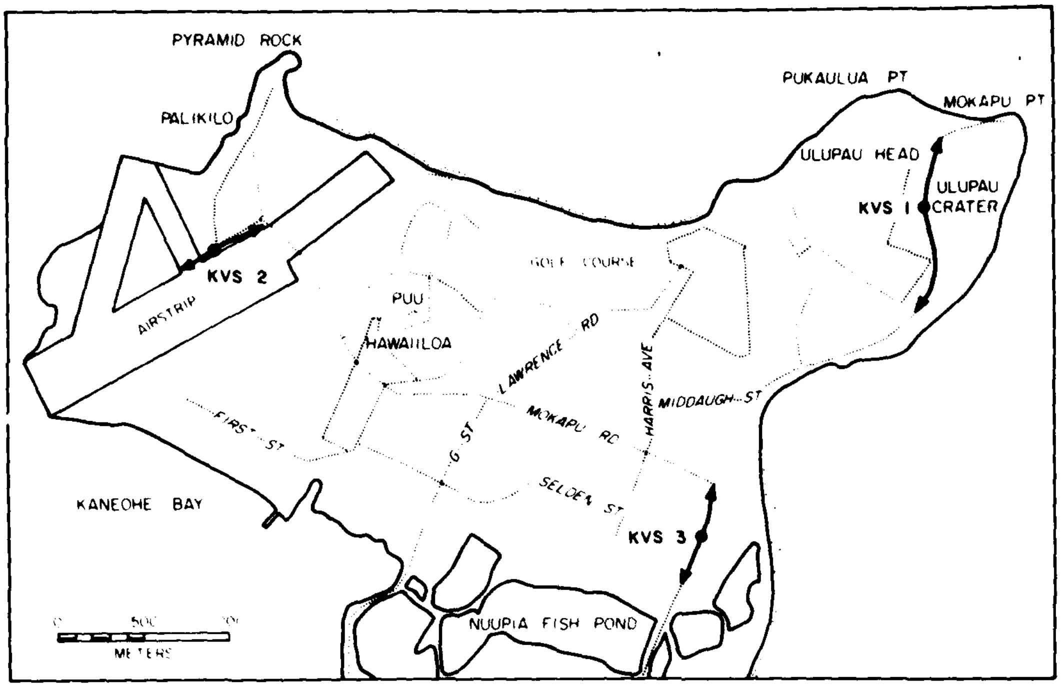

FIGURE 12. Map of Mokapu Peninsula Showing Location of DC Resistivity Soundings.

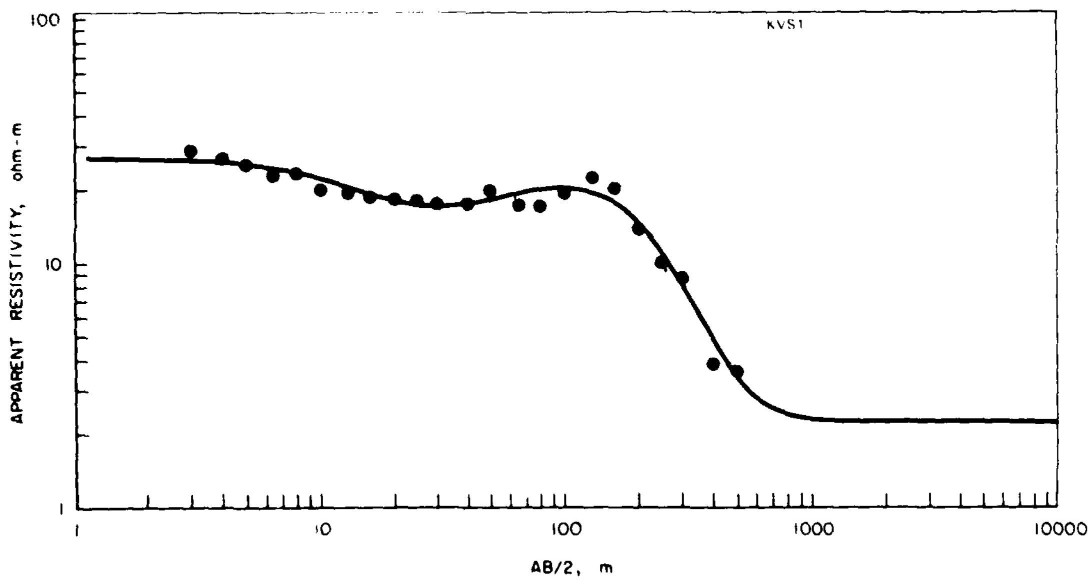

FIGURE 13. Observed (Solid Circles) and Theoretical (Figure 16) Apparent Resistivities for Sounding KVS1.

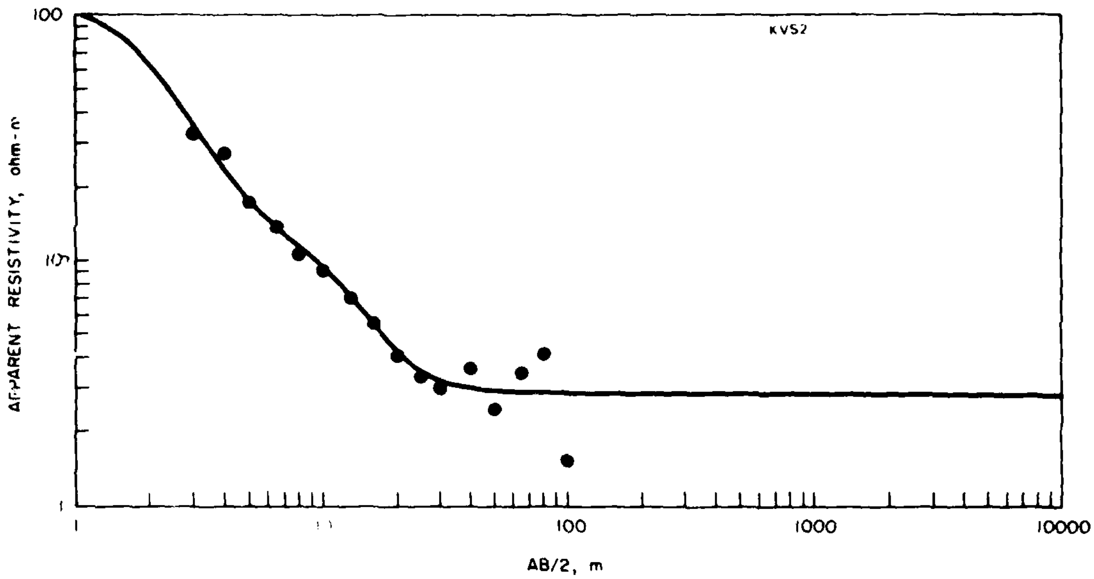

FIGURE 14. Observed (Solid Circles) and Theoretical (Figure 16) Apparent Resistivities for Sounding KVS2.

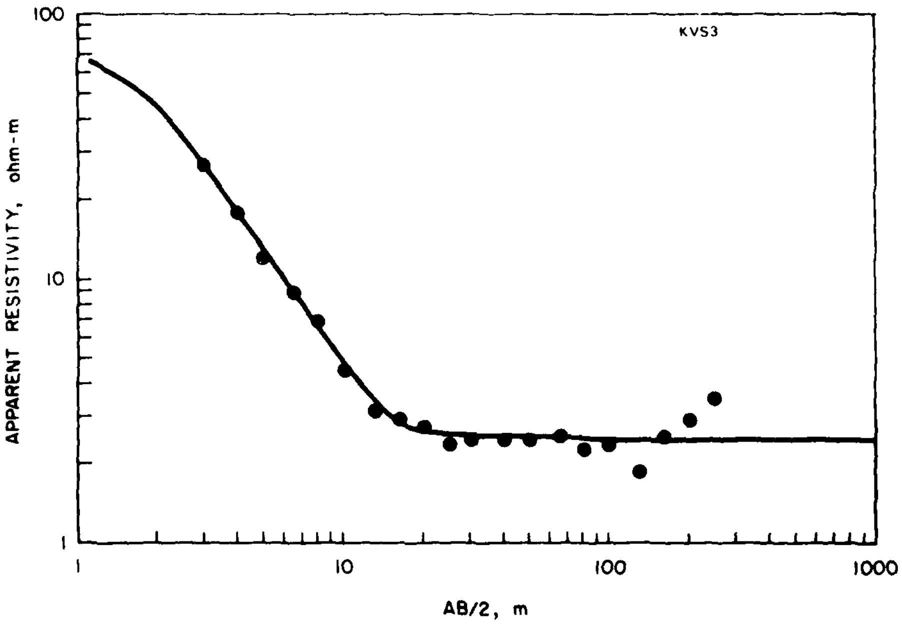

FIGURE 15. Observed (Solid Circles) and Theoretical (Figure 16) Apparent Resistivities for Sounding KVS3.

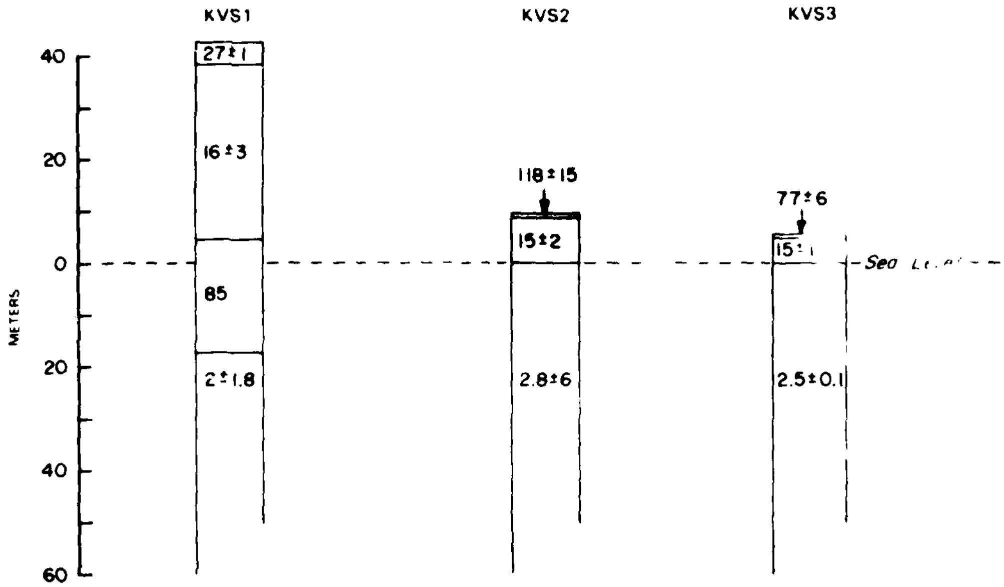

FIGURE 16. Interpreted Resistivity Sections in Ohm-Meters for the Three Soundings.

RESULTS AND DISCUSSION

The geology of the area has been described by Wentworth and Hoffmeister (1939) and more recently by Cox and Sinton. Sounding KVS1 crosses the center of Ulupau Head, a nephelinite tuff cone. Sounding KVS2 is situated on alluvial material but lies close to exposed melilitite basalt flows from Puu Hawaiiloa, whose center lies approximately 1 kilometer east of the sounding site. KVS3 is situated on calcareous and sedimentary material including reef limestone, which constitutes much of the Mokapu Peninsula. That the resistivities both above and below sea level are so similar at the three sites is somewhat unexpected. Wentworth and Hoffmeister (1939) have proposed that the peninsula is underlain by a rock platform whose top is close to present sea level. This platform was thought by them to consist of volcanic material from either Ulupau crater or from the Moku Manu vent, situated several miles to the north of the peninsula.

If basaltic material does underlie the peninsula, the resistivity data strongly suggest elevated temperatures at shallow depth. This theory follows from application of Archies Law to typical Hawaiian basalts using coefficients determined by Rai (1977). The relationship between resistivity and porosity is given by the equation.

$$\rho = 1.17\phi^{-1.42} \quad \text{(Mattice, 1981)}$$

The effect of temperature can be described by an equation given by Darknov (1962), namely

$$\rho_T = \frac{\rho_{20}}{1 + \beta(T - 20)}$$

where ρ_T and ρ_{20} are the resistivities of a rock containing an electrolyte at temperatures T and 20°C respectively. Taking β as 0.025/°C, the following combinations of temperature and porosity would then yield a resistivity of 2.5 ohm-m for seawater-saturated basalt.

Temperature, °C	Porosity
20	0.58
44	0.4
76	0.3
140	0.2

The values in the above table imply that even with relatively high porosities of 0.2 to 0.3, temperatures between 76 and 140°C would be required to give the observed resistivity. However, the low resistivities of 15 ohm-m observed above sea level at all three sites suggest the presence of a large quantity of clay, which has a low intrinsic resistivity in addition to the ability to retain a fairly large quantity of water. If this is the case, the low resistivities observed below sea level could be explained without the need for higher-than-normal temperatures. Zhody and Jackson (1969) give a value of 3 ohm-m for clay saturated with brackish-to-saline water that they observed close to the coast in the Waialua area, about 30 kilometers west of Mokapu Peninsula. The presence of clay to a depth of more than 100 meters below sea level in this area does not have any direct confirmation from other data. However, the post-erosional volcanism that the peninsula experienced is thought to have occurred between the Kahipa (−91 meters) and Kaena (+29 meters) stands of the sea (Winchell, 1947), so the presence of clay to a depth of 100 meters below sea level is not unreasonable.

The high resistivity layer in sounding KVS1 is interpreted to be relatively unweathered Ulupau tuff, which outcrops at the northern end of this sounding. It is probable that this sounding may be severely affected by the lateral boundary between this tuff and the lower resistivity material at the southern end of the sounding. The interpreted one-dimensional vertical section in Figure 16 should therefore be viewed with some suspicion. The KVS1 sounding is also more influenced by the effect of the low resistivity ocean than the other two soundings and will tend to lower the interpreted basement resistivity below the true value by as much as 50%. For soundings KVS2 and KVS3 this reduction should be less than 4% (Mattice, 1981).

CONCLUSIONS

On the basis of the limited resistivity data during the present survey, it is suggested that the Mokapu Peninsula is underlain by a layer of brackish-to-saline water-saturated clay. The resistivity sounding data do not provide any evidence to substantiate the presence of a thermal anomaly beneath the KMCAS.

IV. SUMMARY AND CONCLUSIONS

The present series of field studies conducted on the Mokapu Peninsula and adjacent areas has provided substantial insight into both the structure as well as the geothermal potential within the study area. The available geological data indicate that the post-erosional volcanic vents within and around the peninsula are very old (400,000 years before present) and that they were all isolated and short-lived events. The depths from which the magmas originated, as well as the limited duration of each event, suggest that magma chambers were not associated with the eruptive events and therefore very little thermal energy was deposited in the subsurface environment as a result of the post-erosional activity. Thus the probability that a significant geothermal resource is associated with these events is very small and, although Mokapu is located adjacent to the inferred caldera of Koolau volcano, there is presently little geologic evidence to suggest that remnant heat associated with the Koolau magma chamber is present at economically accessible depths.

The geochemical data acquired within and around Mokapu identified one area on the peninsula in which soil-mercury and radon ground-gas concentrations indicated a low-level anomaly. Although both ground-gas and groundwater anomalies were identified within the inferred boundaries of the Koolau caldera, the magnitude of the anomalies were all considered to be moderate to low. The data obtained on Mokapu Peninsula during the present surveys, therefore, give little indication that a thermal resource is associated with the post-erosional volcanic vents found on the peninsula. However, other data suggest that there is a small but significant probability that a thermal anomaly may be associated with intrusive material within the Koolau caldera to the south of Mokapu.

Schlumberger resistivity soundings completed on Mokapu have indicated that, over most of the peninsula, there is a thin, moderately resistive surface layer underlain by a very low-resistivity basement. Although the resistivity of the basement material is somewhat lower than expected for seawater-saturated basalts, the observed resistivities are consistent with those expected for a seawater-saturated clay layer underlaying the peninsula. It is therefore suggested that the interpreted temperatures beneath the peninsula are within the normally observed ambient range.

On the basis of the data compiled during the present study, it is considered unlikely that exploitable temperatures would be encountered at economically viable depths beneath the Mokapu Peninsula. The data do suggest, however, that a low-temperature resource may be associated with the Koolau caldera. Further, more detailed, geophysical and geochemical surveys would be required before it would be possible to confirm this preliminary conclusion.

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